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Low-cost and high-efficiency automated tensiometer for real-time irrigation monitoring[1]

Tensiômetro automatizado de baixo custo e alta eficiência para monitoramento da irrigação em tempo real

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HIGHLIGHTS:

A high correlation between the pressure sensor and tensiometer data allows for better irrigation control at a low cost.
Real-time monitoring through constant data acquisition favors irrigation self-programming.
Mechanical equipment combined with sensor reading can be a feasible alternative for farmers.

ABSTRACT: Knowing the soil moisture available to plants is important for adequate management of water use in agricultural farms, with automated methods being the most accurate. However, acquisition costs are high and most of the commercially available irrigation controllers still work using pre-set times. This study aimed to develop and calibrate a low-cost automated tensiometer with high efficiency in irrigation control, based on real-time monitoring. The research was conducted at the Laboratories of Hydraulics and of Water Soil Plant and Atmosphere Relationship, which belong to the Federal University of Grande Dourados (UFGD), in Dourados, MS, Brazil, with soil classified as an Oxisol. Pressure transducers and a microcontroller were used to assimilate the pressure inside tensiometers and transform it into readings of soil water matric potential (Ψm). Thus, the calibration was carried out by comparing the different readings of the transducer and digital tension meter. Different tensions were applied to obtain a soil moisture curve, starting from the most humid point (saturated) to the driest one (oven-dried soil), collecting 20 valid points. Subsequently, the data were subjected to the normality test, with subsequent statistical analysis and regression curve models. Linear adjustments with a high coefficient of determination (R^2 = 0.99) were observed, with the automated system built in this study being capable of monitoring soil water tension in real-time.

Key words: volumetric humidity, sensor 'MPX', water management, microcontroller, Arduino

RESUMO: Conhecer a umidade de solo disponível para as plantas é preponderante para o manejo adequado do uso da água nas propriedades agrícolas, sendo os métodos automatizados os mais precisos. Entretanto, os custos de aquisição são elevados e a maioria dos controladores de irrigação ainda trabalha com tempos pré-definidos. Assim, o estudo teve por objetivo desenvolver e calibrar um tensiômetro automatizado de baixo custo e alta eficiência no controle da irrigação, baseado em monitoramento em tempo real. A pesquisa foi conduzida nos Laboratórios de Hidráulica e Relação Água-Solo-Planta-Atmosfera pertencentes à Universidade Federal da Grande Dourados (UFGD), em Dourados, MS, com solo classificado como Oxisol. Foram utilizados transdutores de pressão e um microcontrolador capazes de assimilar a pressão no interior dos tensiômetros e transformá-la em leituras de potencial matricial de água no solo - Ψm. Desta forma, realizou-se a calibração comparando as diferentes leituras do transdutor e do tensímetro digital de agulha. Foram aplicadas diferentes tensões para obtenção da curva de umidade do solo, partindo do ponto mais úmido (saturado) para o mais seco (solo seco em estufa), coletando 20 pontos válidos. Posteriormente, os dados foram submetidos ao teste de normalidade, com posterior análise estatística e modelos de curva de regressão. Foram verificados ajustes lineares com altos valores de coeficiente de determinação (R^2 = 0,99), sendo o sistema automatizado construído, capaz de monitorar a tensão de água do solo em tempo real.

Palavras-chave: umidade volumétrica, sensor 'MPX', manejo da água, microcontrolador, Arduino

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Introduction

Technology is used in different sectors, such as agriculture. Innovations in rural areas have pointed to precision agriculture as a common practice in the future (Lowenberg-Deboer et al., 2020). Studies carried out by the United Nations have shown the growth of the world population to 9.5 billion in 2050, bringing debates about the risk of food insecurity (Saath & Fachinello, 2018), leaving agriculture to absorb this growth sustainably.

According to the National Water Agency (ANA, 2019), several Brazilian regions have a water deficit. Thus, techniques that minimize the effect of this deficit are necessary, offering higher security to the production sectors (Grisa et al., 2019). Irrigation non-management for most producers results in water waste (Cunha & Rocha, 2015).

According to Buttaro et al. (2015), most of the soil water monitoring systems are expensive and non-usual, thus there is resistance from producers to using these techniques (Vorpagel et al., 2017). The matric potential is the main component of reading regarding soil water movement (Melo Filho et al., 2015; Tsai et al., 2020). Thus, the creation of tools capable of carrying out this measure is widespread in the world (Vaz et al., 2013; Kim et al., 2015). According to Gomes & Roland (2018), an alternative widely adopted by rural producers is the use of tensiometers, a simple and easy-to-install technology.

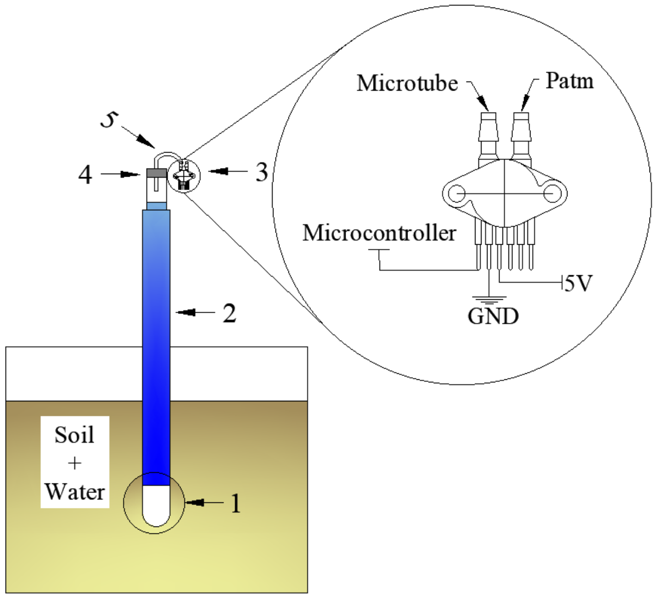
Studies using mechanical and or electronic/automated tensiometers to determine soil moisture (Thalheimer, 2013; Arruda et al., 2017; Abd El-Baset et al., 2018; Goodchild et al., 2018; Li et al., 2020; Pereira et al., 2020) have shown a reduction in labor and volume of applied water, increasing the system efficiency. Furthermore, although automated tensiometers can be simple to use and low cost for farmers, most commercial irrigation controllers connected by soil sensors are programmable with only fixed times. Therefore, they may disregard changes in soil moisture or water potential levels.

In this context, the study aimed to develop and calibrate a low-cost automated tensiometer with high efficiency of irrigation control based on real-time monitoring.

Material and Methods

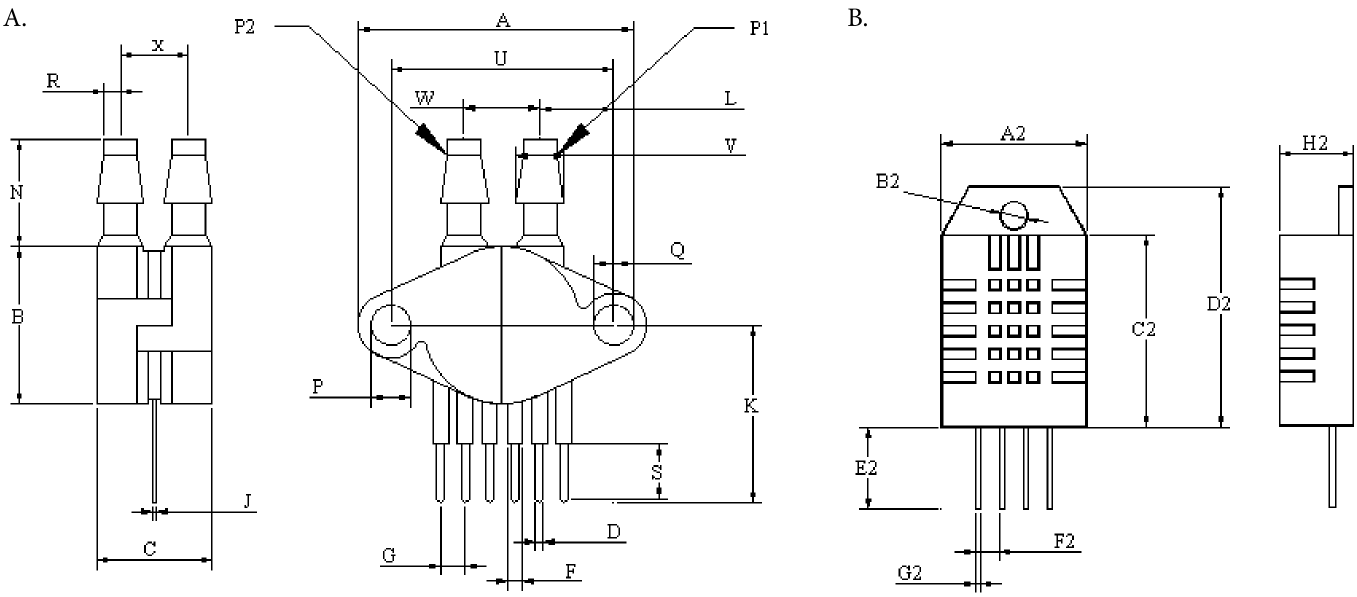
The study was carried out in the Laboratories of Hydraulics and of Water Soil Plant and Atmosphere Relationship (RASPA) of the Federal University of Grande Dourados (UFGD), Dourados, MS, Brazil (22° 11' 46.9" S and 54° 56' 03" W, with an altitude of 437 m). The automated tensiometer consisted of a 1/2" PVC tube 0.45 m long with a porous capsule at one end and an electronic circuit with a pressure sensor (pressure transducer) at the other end. The tensiometers were buried 20 cm in a container filled with the soil of the region, classified as Oxisol with 61.3% clay, 25.1 silt, and 13.6 sand (Figure 1).

The Motorola MPX5100dp pressure sensor (Motorola, 1995) was used associated with the tensiometer (Figure 2A), as it has a reading range from 0 to 100 kPa and a relatively



1 - Porous capsule; 2 - PVC tube; 3 - Pressure sensor MPX5100dp; 4 - Sealing rubber; 5 - Microtube; Patm - Atmospheric pressure; GND - Ground

Figure 1. Model of the automated tensiometer



Dimensions in mm: (A) A - 29.85, B - 18.16, C - 11.05, D - 0.84, F - 1.63, G - 2.54, J - 0.41, K - 18.42, L - 7.62, N - 11.18, P - Ø4.04, Q - Ø4.04, R - 2.11, S - 6.10, U - 23.11, V - 4.93, W - 8.38, and X - 7.06; (B) A2 - 15.10, B2 - Ø3.00, C2 - 20.00, D2 - 25.10, E2 - 8.50, F2 - 2.00, G2 - 0.50, and H2 - 7.70

P1 – Port positive pressure; P2 – Port vacuum

Figure 2. MPX5100DP pressure sensor and DHT22 temperature and moisture sensor

low market cost (around US$12.00), meeting the management requirements proposed in the project. This sensor acts as a differential pressure sensor between two points (P1 and P2), consisting of a silicon diaphragm, which deforms according to the stress induced by the pressure of an external agent, causing an analog signal proportional to the pressure exerted on the diaphragm. Thus, it allowed the pressure inside the tensiometer to be directly correlated with the analog signal emitted by the sensor. In addition to the pressure sensor, the DHT22 temperature and moisture sensor (Figure 2B) was used to provide temperature and moisture information to the MPX5100dp sensor, considering that the pressure sensor is influenced by temperature. The total cost of the system was approximately US$40.00.

The electrical circuit for the construction of the data acquisition system consisted of a 1600-point protoboard, an UNO Smd Atemega328 microcontroller, responsible for controlling and integrating the system components, an MPX5100dp differential pressure sensor, a DHT22 temperature and moisture sensor, responsible for providing the temperature variable necessary for the software to perform the reading corrections suggested by the manufacturer, and an Arduino micro SD card module for data storage.

Four buckets with a perforated bottom and a volume of 22 dm^3 were used in the tests, where the soil was placed to maintain its original structure (Figure 3).

Two tensiometers were placed in each bucket during soil filling, one for sensor use (MPX5100dp) and another for backup, if necessary. After filling, the soil was saturated daily for three days for its homogeneous sealing (filling and juxtaposition of soil around the tensiometers) in the container.

Subsequently, the soil was dried to simulate various soil moisture conditions, thus creating a calibration curve for adjusting the readings performed by the pressure sensor from saturation (0 kPa) until the soil was under conditions close to the minimum matric capacity supported by a tensiometer without the water column breaking, that is, around −75 kPa. The drying process was carried out using a forced circulation oven, where the samples were maintained for 24 hours at 50 °C, followed by the reading of data from the electronic sensor and a digital tension meter (digital needle tensimeter from the company Sonda Terra®), which was plugged on the sealing rubber at the top of the tensiometer. All the readings were carried out at 4:00 p.m.

To correlate tension and moisture, current moisture (θa) was estimated using the soil water retention curve obtained by tension table and Richards extractor in the RASP Laboratory, with adjustment by van Genuchten (1980) equation:

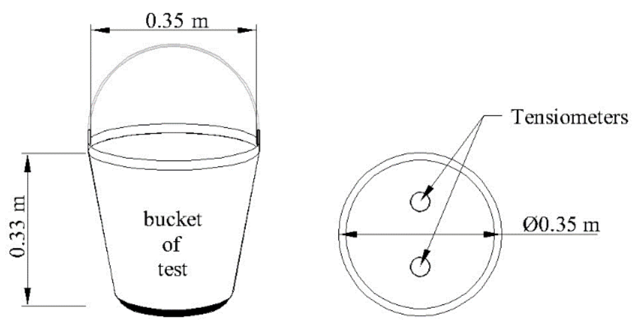


Figure 3. Arrangement of tensiometers

$$\theta c = 0.152 + \frac{(0.609 - 0.152)}{\left[1 + \left(50.168 \psi_{mc}\right)^{1.056}\right]^{0.108}} \quad \left(R^2 = 1.00 \text{ and } p < 0.01\right) \tag{1}$$

$\theta r = 0.152$ cm^3 cm^{-3}; $\theta s = 0.609$ cm^3 cm^{-3};

where:

θc - current volumetric soil moisture (cm^3 cm^{-3});

θr - residual volumetric soil moisture (cm^3 cm^{-3});

θs - volumetric soil moisture at the saturation point (cm^3 cm^{-3}); and,

Ψ_{mc} - current soil water matric potential (kPa).

The equation used to convert the analog/digital signal of the MPX5100DP sensor was created from the information provided by the manufacturer:

$$P = \frac{\left[(Vsen - Vout) \pm (PE \cdot TF \cdot 0.009 \cdot VS) - (VS \cdot 0.04)\right]}{9.207} \tag{2}$$

where:

Vsen - value read by the MPX5100DP sensor in the analog format;

Vout - the difference between the minimum and maximum output tension of the sensor;

PE - pressure error equal to 2.5, according to the manufacturer;

TF - temperature factor;

VS - Output voltage, equal to 1023 bits; and,

P - pressure in kPa.

Calibration was performed by comparing the different readings between the transducer and the digital tension meter. Different tensions were applied through the drying of the soil, starting with its saturation, and then performing its drying using an oven, collecting 20 valid points (discarding sudden variations).

Subsequently, the data were subjected to the normality test using a MS Excel® spreadsheet and the ActionStat, with the following quantitative and descriptive analyses:

1) Separation of data by sensors (Sensor 1, Sensor 2, Sensor 3, and Sensor 4) to detect differences in the data evaluated at each moisture point during the drying process. The data were then grouped according to the treatments (sensor and tensimeter) to detect differences in the evaluated variables.

2) Application of the Anderson-Darling test to verify whether the data adjusts to the normal distribution.

3) F-test for variances to find possible differences between the data and allow choosing the appropriate t-tests.

4) t-test of two samples to verify differences when comparing treatments.

Finally, regression models were constructed to determine the linear calibration equation (Eq. 3):

$$S = a \cdot TD + b \tag{3}$$

where:

S - MPX pressure sensor reading (kPa);

a and b - linear coefficient and intercept, respectively (dimensionless); and,

TD - digital tension meter reading (kPa).

Results and Discussion

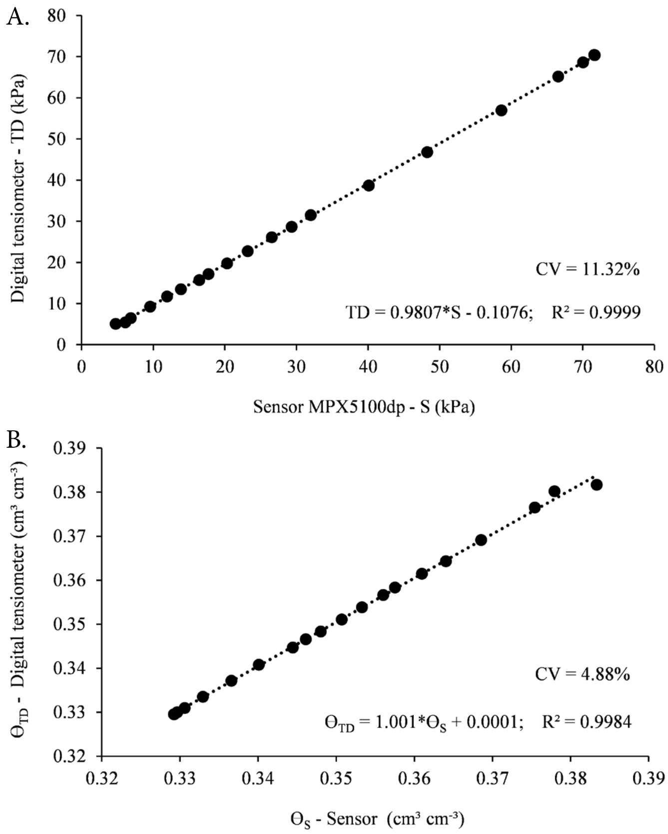
The sensors showed similar tension values during the experimental test, but small fluctuations were observed, as predicted in other studies on pressure sensor calibration (Pereira et al., 2020). Fluctuation errors occur due to ambient temperature variation, causing expansion or contraction of the air present inside the tensiometer (Brito et al., 2014). The data from readings performed by the four sensors were grouped to minimize the effects of fluctuation, and the moving average filter, which presents good results in studies with a large volume of data readings, was also used (Pacheco et al., 2017).

The data were not transformed, as it showed a normal distribution. The F test for variance showed values lower than the critical F ($p \geq 0.05$) for the four observations (sensor and tensimeter), resulting in equal variances with the homoscedastic t-test, with no differences between the means of S (MPX5100dp sensor) and TD (digital tensimeter).

The t-test applied to equal variances in the tension data obtained with the sensor and the tensimeter showed no differences between the observations means at $p > 0.05$.

The t-test was again applied to the grouped data, as shown in Table 1, showing no differences between the sample means ($p > 0.05$). It showed values lower than the critical F ($p > 0.05$), as observed for the F test for variance.

Scatter plots were constructed after data analysis, with the linear regression analysis of each observation. The general scatter plot was also applied to the mean data of the four observations with linear adjustment. Figure 4A shows the comparison of pressure in kPa of readings obtained through automated tensiometers with the sensor associated with the readings of the digital tensiometer, demonstrating the relationship between them. Figure 4B shows the volumetric moisture θ (cm³ cm⁻³) of the equipment readings, considering the soil water retention curve (Figure 5).



* - Significant at $p \leq 0.05$ by F test; CV - Coefficient of variation; R^2 - Coefficient of determination

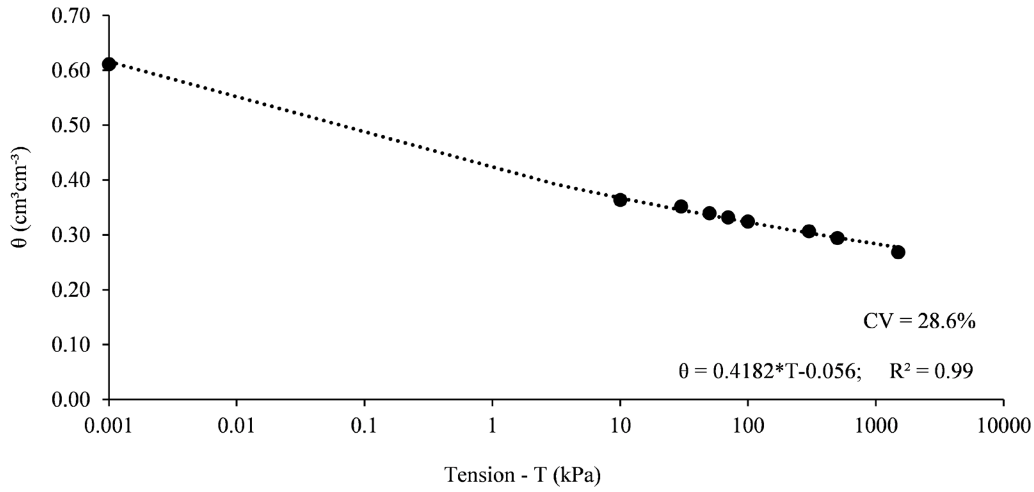
Figure 4. Mean calibration curves of the sensors (A) and calibration curve based on the volumetric moisture (B)

Figure 4 shows high coefficients of determination ($R^2 = 0.99$), which are related to the high precision of the sensor. Arruda et al. (2017) idealized a tensiometer with a

Table 1. Validation of the calibration equation

Data	TD (kPa)	MPX5100dp (kPa) (S)	error (kPa²) (TD-S)	S adjusted (kPa)	error (kPa²) (S–S adjusted)
1	5.1150	4.7300	0.1482	4.5308	0.3413
2	5.4775	6.1000	0.3875	5.8744	0.1575
3	6.5175	6.8700	0.1243	6.6295	0.0125
4	9.2925	9.5600	0.0716	9.2676	0.0006
5	11.7575	11.9025	0.0210	11.5649	0.0371
6	13.5275	13.8550	0.1073	13.4797	0.0023
7	15.7625	16.4350	0.4523	16.0099	0.0612
8	17.1850	17.7100	0.2756	17.2603	0.0057
9	19.7925	20.3175	0.2756	19.8175	0.0006
10	22.7450	23.1700	0.1806	22.6149	0.0169
11	26.1725	26.5625	0.1521	25.9419	0.0532
12	28.6700	29.3200	0.4225	28.6462	0.0006
13	31.5200	31.9800	0.2116	31.2549	0.0703
14	38.7375	40.1125	1.8906	39.2304	0.2430
15	46.7950	48.2575	2.1389	47.2182	0.1791
16	56.9450	58.6300	2.8392	57.3905	0.1985
17	65.2175	66.5575	1.7956	65.1650	0.0028
18	68.6575	70.0050	1.8158	68.5460	0.0124
19	70.4300	71.5825	1.3283	70.0931	0.1135
20	70.3775	71.6500	1.6193	70.1593	0.0476
Mean	31.5	32.3			
Variance	546.5477	568.1959			
SD	23.3784	23.8369			
F test p	0.933				
t-test p	0.923				

SD – Standard deviation; TD – Digital tensiometer; S – Standard error



* - Significant at p ≤ 0.05 by F test

Figure 5. Soil water retention curve

pressure transducer that showed good results in a controlled environment, with $R^2 = 0.99$. The authors also stated that the system had advantages such as the possibility of reading and storing data, assisting the farmer in making decisions regarding the management of irrigation, with the possibility of automation.

Sadeghi et al. (2020) developed a relatively inexpensive and simple-to-use vacuum tensiometer (CRT) to monitor soil water pressure, using a linear calibration pressure transducer with $R^2 = 0.98$. Mendes et al. (2019) built an ultra-high capacity tensiometer with linear adjustment of $R^2 = 1$ for water pressure and tension.

Table 1 shows that the differences between readings become more pronounced above 38 kPa, reaching close to 2.9 kPa between each reading. However, the error (S–S adjusted) did not reach 0.25 kPa, with an insignificant variation in soil water tension, demonstrating a high precision when the equation was used. Thus, the calibration equation satisfies the requirements for monitoring soil water for irrigation, as the field capacity is in the range from 6 to 33 kPa for characteristic soils of the Mato Grosso do Sul state, Brazil (Filguerias et al., 2016).

The adjustment equation can be implemented to the Arduino sketch by adjusting the pressure sensor reading and providing the actual pressure values. Thus, the soil water retention curve allows estimating the amount of water available in the soil because the tensiometer has a small matric tension range (0 to 80 kPa) (Brito et al., 2009; Groppo et al., 2019), but it covers the field capacity of the characteristic soil of the region, thus meeting the requirements of irrigation management.

Conclusions

1. The electronic system has a high coefficient of determination between the sensor and digital tensiometer readings.

2. The pressure transducer was reliable in measuring pressure with non-significant errors, which allows accurate readings.

3. The automated tensiometer was technically feasible for real-time monitoring of soil moisture.

Acknowledgements

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